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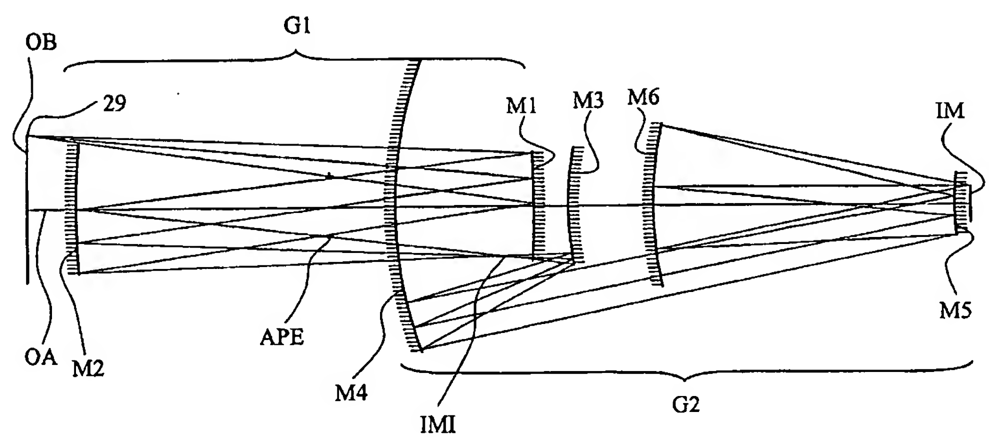

(57) Abstract: An EUV optical projection system includes at least six reflecting surfaces for imaging an object (OB) on an image (IM). The system is preferably configured to form an intermediate image (IMI) along an optical path from the object (OB) to the image (IM) between a secondary mirror (M2) and a tertiary mirror (M3), such that a primary mirror (M1) and the secondary mirror (M2) form a first optical group (G1) and the tertiary mirror (M3), a fourth mirror (M4), a fifth mirror (M5) and a sixth mirror (M6) form a second optical group (G2). The system also preferably includes an aperture stop (APE) located along the optical path from the object (OB) to the image (IM) between the primary mirror (M1) and the secondary mirror (M2). The secondary mirror (M2) is preferably concave, and the tertiary mirror (M3) is preferably convex. Each of the six reflecting surfaces preferably receives a chief ray (CR) from a central field-point at an incidence angle of less than substantially 15°. The system preferably has a numerical aperture greater than 0.18 at the image (IM). The system is preferably configured such that a chief ray (CR) converges toward the optical axis (OA) while propagating between the secondary mirror (M2) and the tertiary mirror (M3).

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PROJECTION SYSTEM FOR EUV LITHOGRAPHY

BACKGROUND OF THE INVENTION:

1. Field of the Invention

The invention relates to an optical projection system for extreme ultraviolet (EUV) lithography, particularly including six mirrors arranged in two optical groups.

2. Description of the Related Art

It is widely accepted that current deep ultraviolet (DUV) projection printing systems used in a step and scan mode will be able to address the needs of the semiconductor industry for the next two or three device nodes. The next generation of photolithographic printing systems will use exposure radiation having soft x-ray or extreme ultraviolet wavelengths of approximately 11 nm to 15 nm, also in a step and scan printing architecture. To be economically viable, these next generation systems will require a sufficiently large numerical aperture to address sub 70 nm integrated circuit design rules. Further, these photolithography systems will require large fields of view in the scan direction to ensure that the throughput (defined in terms of wafers per hour) is sufficiently great so that the process is economically viable.

The theoretical resolution (R) of a lithographic printing system can be expressed by the well-known relationship $R=k_1\lambda/NA$, where k_1 is a process dependent constant, λ is the wavelength of light, and NA is the numerical aperture of the projection system. Knowing that EUV resists support a k_1-factor of ~0.5 and assuming a numerical aperture of 0.20, an EUV projection system can achieve a theoretical resolution on the order of approximately 30 nm with $\lambda = 13.4$ nm. It is recognized in the present invention that all reflective projection systems for EUV lithography for use in a step and scan architecture having both a large numerical

aperture (0.20 to 0.30) and a large field (2 to 3 mm) are desired to address the sub-50 nm linewidth generations as defined by the International Sematech's International Technology Roadmap for Semiconductors (1999).

Four-mirror projection systems, such as those described in United States patents no. 5,315,629 and 6,226,346, issuing to Jewel and Hudyma, respectively, lack the degrees of freedom necessary to correct aberrations over a sufficiently large NA to achieve 30 nm design rules. The '346 patent teaches that a four-mirror projection system can be used to correct aberrations at a numerical aperture up to 0.14 (50 nm design rules). However, it is desired that the width of the ring field be reduced to enable wavefront correction to the desired level for lithography. The '346 patent demonstrates that the ring field is reduced from 1. 5 mm to 1.0 mm as a numerical aperture is increased from 0.10 to 0.12. Further scaling of the second embodiment in the' 346 patent reveals that the ring field must be reduced to 0.5 mm as a numerical aperture is increased further to 0.14. This reduction in ring field width results directly in reduced throughput of the entire projection apparatus. Clearly, further advances are needed.

Five-mirror systems, such as that set forth in United States patent no. 6,072,852, issuing to Hudyma, have sufficient degrees of freedom to correct both the pupil dependent and field dependent aberrations, thus enabling numerical apertures in excess of 0.20 over meaningful field widths (> 1.5 mm). While minimizing the number of reflections has several advantages particular to EUV lithography, an odd number of reflections create a problem in that new stage technology would need to be developed to enable unlimited parallel scanning. To "unfold" the system to enable unlimited synchronous parallel scanning of the mask and image with existing scanning stage technologies, it is recognized herein that an additional mirror should be incorporated into the projection system.

Optical systems for short wavelength projection lithography utilizing six or more reflections have been disclosed in the patent literature. One such early system is disclosed in U.S. Pat. No. 5,071,240, issuing to Ichihara and Higuchi entitled,

"Reflecting optical imaging apparatus using spherical reflectors and producing an intermediate image." The '240 patent discloses a 6-mirror catoptric or all-reflective reduction system utilizing spherical mirrors. This particular embodiment is constructed with three mirror pairs and uses positive/negative (P/N) and negative/positive (N/P) combinations to achieve the flat field condition. Ichihara and Higuchi also demonstrate that the flat field imaging condition (zero Petzval sum) can be achieved with a system that utilizes an intermediate image between the first mirror pair and last mirror pair. The patent teaches the use of a convex secondary mirror with an aperture stop that is co-located at this mirror. It is also clear from examination of the embodiments that the '240 patent teaches the use of low incidence angles at each of the mirror surfaces to ensure compatibility with reflective coatings that operate at wavelengths around 10 nm.

While the embodiments disclosed in the '240 patent appear to achieve their stated purpose, these examples are not well suited for contemporary lithography at extreme ultraviolet wavelengths. First, the systems are very long (~ 3000 mm) and would suffer mechanical stability problems. Second, the embodiments do not support telecentric imaging at the image which is desired for modern semiconductor lithography printing systems. Lastly, the numerical aperture is rather small (~ 0.05) leaving the systems unable to address 30 nm design rules.

Recently, optical projection production systems have been disclosed that offer high numerical apertures with at least six reflections designed specifically for EUV lithography. One such system is disclosed in United States patent number 5,815,310, entitled, "High numerical aperture ring field optical projection system," issuing to Williamson. In the '310 patent, Williamson describes a six-mirror ring field projection system intended for use with EUV radiation. Each of the mirrors is aspheric and share a common optical axis. This particular embodiment has a numerical aperture of 0.25 and is capable of 30 nm lithography using conservative (~0.6) values for k_1. The '310 patent suggests that both PNPPNP and PPPPNP reimaging configurations are possible with a physically accessible intermediate image

located between the third and fourth mirrors. This particular embodiment consists, from long conjugate to short conjugate, of a concave, convex, concave, concave, convex and concave mirror, or PNPPNP for short. The '310 patent suggests that both PNPPNP and the PPPPNP power distributions can achieve 30 nm design rules.

The preferred EUV embodiment disclosed in the '310 patent suffers from several drawbacks, one of which is the high incidence angles at each of the mirrored surfaces, particularly on mirrors M2 and M3. In some instances, the angle of incidence exceeds 24° at a given location on the mirror. Both the mean angle and deviation or spread of angles at a given point on a mirror surface is sufficient to cause noticeable amplitude and phase effects due to the EUV multilayer coatings that might adversely impact critical dimension (CD control).

Two other catoptric or all-reflective projection systems for lithography are disclosed in United States patent number 5,686,728 entitled, "Projection lithography system and method using all-reflective optical elements," issuing to Shafer. The '728 patent describes an eight mirror projection system with a numerical aperture of about 0.50 and a six-mirror projection system with a numerical aperture of about 0.45 intended for use at wavelengths greater than 100 nm. Both systems operate in reduction with a reduction ratio of 5x. Like the systems described in the '310 patent, these systems have an annular zone of good optical correction yielding lithography performance within an arcuate shaped field. While these systems were designed for DUV lithography and are fine for that purpose, these embodiments make very poor EUV projection systems. Even after the numerical aperture is reduced from 0.50 to 0.25, the incidence angles of the ray bundles are very large at every mirror including the mask, making the system incompatible with either Mo/Si or Mo/Be multilayers. In addition, both the aspheric departure and aspheric gradients across the mirrors are rather large compared to the EUV wavelength, calling into question whether or not such aspheric mirrors can be measured to a desired accuracy for EUV lithography. Recognizing these issues, the '728 patent explicitly teaches away from using

catoptric or all-reflective projection systems at EUV wavelengths and instead restricts their use to longer DUV wavelengths.

Another projection system intended for use with EUV lithography is disclosed in U.S. Patent No. 6,033,079, issuing to Hudyma. The '079 patent entitled, "High numerical aperture ring field projection system for extreme ultraviolet lithography," describes two preferred embodiments. The first embodiment that the '079 patent describes is arranged with, from long to short conjugate, a concave, concave, convex, concave, convex, and concave mirror surfaces (PPNPNP). The second preferred embodiment from the '079 patent has, from long to short conjugate, a concave, convex, convex, concave, convex, and concave mirror surfaces (PNNPNP). The '079 patent teaches that both PPNPNP and PNNPNP reimaging configurations are advantageous with a physically accessible intermediate image located between the fourth and fifth mirror. In a manner similar to the '240 and '310 patents, the '079 patent teaches the use of an aperture stop at the secondary mirror and a chief ray that diverges from the optical axis after the secondary mirror.

The '079 patent teaches that the use of a convex tertiary mirror enables a large reduction in low-order astigmatism. This particular arrangement of optical power is advantageous for achieving a high level of aberration correction without using high incidence angles or extremely large aspheric departures. For both embodiments, all aspheric departures are below 15 μm and most are below 10 μm. Like the '240 patent, the '079 patent makes a significant teaching related to EUV via the use of low incidence angles on each of the reflective surfaces. The PPNPNP and PNNPNP power arrangements promote low incidence angles thus enabling simple and efficient EUV mirror coatings. The low incidence angles work to minimize coating-induced amplitude variations in the exit pupil, minimize coating-induced phase or optical path difference (OPD) variations in the exit pupil, and generally lower the tolerance sensitivity of the optical system. These factors combine to promote improved transmittance and enhanced CD uniformity in the presence of variations in focus and exposure.

While the prior art projection optical systems have proven adequate for many applications, they're not without design compromises that may not provide an optimum solution in all applications. Therefore, there is a need for a projection optical system that can be used in the extreme ultraviolet (EUV) or soft X-ray wavelength region that has a relatively large image field with capable of sub 50 nm resolution.

SUMMARY OF THE INVENTION:

In view of the above, an EUV optical projection system is provided including at least six reflecting surfaces for imaging an object on an image. The system is configured to form an intermediate image along an optical path from the object to the image between a secondary mirror and a tertiary mirror, such that a primary mirror and the secondary mirror form a first optical group and the tertiary mirror and a fourth mirror, a fifth mirror and a sixth mirror form a second optical group. The secondary mirror is concave, and the tertiary mirror is convex.

The system may further include an aperture stop located along the optical path from the object to the image between the primary mirror and the secondary mirror. This aperture stop may be disposed off each of the first mirror and the second mirror.

The system may be further configured such that a chief ray from a central field point converges toward or propagates approximately parallel to the optical axis while propagating between the secondary mirror and the tertiary mirror. The primary mirror may be physically located closer to the object than the tertiary mirror.

The system may be further configured such that a chief ray from a central field point diverges away from the optical axis while propagating between the secondary mirror and the tertiary mirror. The tertiary mirror may be physically located closer to the object than the primary mirror.

The primary mirror is preferably concave, the fourth mirror is preferably concave, the fifth mirror is preferably convex and the sixth mirror is preferably concave.

The physical distance between the object and the image may be substantially 1500 mm or less, and may further be substantially 1200 mm or less.

The system preferably has a numerical aperture at the image greater than 0.18.

Each of the six reflecting surfaces preferably receives a chief ray from a central field point at an incidence angle of less than substantially 15°, preferably less than substantially 15°, and five of the six reflecting surfaces preferably receives a chief ray from a central field point at an incidence angle of less than substantially 11°, preferably less than substantially 9°.

The system is preferably configured to have a RMS wavefront error of 0.017λ or less, and may be between 0.017λ and 0.011λ.

BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 shows a plan view of an EUV optical projection system according to a first preferred embodiment.

Figure 2 schematically illustrates the geometry of the arcuate ring field according to the preferred embodiments at the object.

Figure 3 shows a plan view of an EUV optical projection system according to a second preferred embodiment.

Figure 4 shows a plan view of an EUV optical projection system according to a third preferred embodiment.

INCORPORATION BY REFERENCE:

What follows is a cite list of references which, in addition to that which is described in the background and brief summary of the invention above, are hereby incorporated by reference into the detailed description of the preferred embodiments, as disclosing alternative embodiments of elements or features of the preferred

embodiment not otherwise set forth in detail below. A single one or a combination of two or more of these references may be consulted to obtain a variation of the preferred embodiments described below. Further patent, patent application and non-patent references, and discussion thereof, cited in the background and/or elsewhere herein are also incorporated by reference into the detailed description of the preferred embodiments with the same effect as just described with respect to the following references:

U.S. patents no. 5,063,586, 5,071,240, 5,078,502, 5,153,898, 5,212,588, 5,220,590, 5,315,629, 5,353,322, 5,410,434, 5,686,728, 5,805,365, 5,815,310, 5,956,192, 5,973,826, 6,033,079, 6,014,252, 6,188,513, 6,183,095, 6,072,852, 6,142,641, 6,226,346, 6,255,661 and 6,262,836;

European patent applications no. 0 816 892 A1 and 0 779 528 A; and

"Design of Reflective Relay for Soft X-Ray Lithography", J. M. Rodgers, T.E. Jewell, International Lens Design Conference, 1990;

"Reflective Systems design Study for Soft X-ray Projection Lithography", T.E. Jewell, J.M. Rodgers, and K.P. Thompson, J. Vac. Sci. Technol., November/December 1990.

"Optical System Design Issues in Development of Projection Camera for EUV Lithography", T.E. Jewell, SPIE Volume 2437, pages 340-347;

"Ring-Field EUVL Camera with Large Etendu", W.C. Sweatt, OSA TOPS on Extreme Ultraviolet Lithography, 1996; and

"Phase Shifting Diffraction Interferometry for Measuring Extreme Ultraviolet Optics", G.E. Sommargaren, OSA TOPS on Extreme Ultraviolet Lithography, 1996;

"EUV Optical Design for a 100 nm CD Imaging System", D.W. Sweeney, R. Hudyma, H.N. Chapman, and D. Shafer, SPIE Volume 3331, pages 2-10.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS:

Three specific preferred embodiments relating to this optical projection system are described.

First Preferred Embodiment:

Figure 1 shows a plan view of a first preferred embodiment, and, taking in conjunction with Table 1 and Table 2, provides an illustrative, exemplary description of this embodiment. Light impinges on an object, e.g. a reflective mask or reticle from an illumination system and is directed to concave mirror M1 after which it reflects from the mirror M1 and passes through a physically accessible aperture stop APE that is located between Mirror M1 and M2. This aperture stop APE is located a substantial distance from the first concave mirror M1 and, likewise, this aperture stop APE is located a substantial distance from concave mirror M2. After the illumination reflects off concave mirror M2, the light comes to a focus at an intermediate image IMI that is located in close proximity to convex mirror M3. From mirror M3 the illumination is directed toward concave mirror M4 where the light is nearly collimated and directed toward convex mirror M5. Upon reflection from mirror M5, the light impinges on concave mirror M6 where it is reflected in a telecentric manner (the chief rays are parallel to the optical axis OA) and focused on the image IM. A semiconductor wafer is typically arranged at the position of the image IM. Since a concave optical surface has positive optical power (P) and a convex optical surface has negative optical power (N), this present embodiment may be characterized as a PPNPNP configuration.

Although there are many ways to characterize this optical system, one convenient way is to break the system into two groups G1 and G2. Starting at the object OB, the first group G1 is comprised the concave mirror pair M1 and M2. This group forms an intermediate image IMI at a magnification of about -0.8x between

mirror M2 and mirror M3. The remaining four mirrors (convex mirror M3, concave mirror M4, convex mirror M5 and concave mirror M6) comprise the second imaging or relay group G2. This second group G2 works at a magnification of approximately -0.3x, resulting in 4x reduction (the reduction ratio is the inverse of the absolute value of the optical magnification) of the object OB at the image IM.

The optical prescription of the first embodiment of Fig. 1 is listed in Table 1 and Table 2. The aspheric mirror surfaces are labeled A(1)-A(6) in the tables with A(1) corresponding to mirror M1, A(2) corresponding to mirror M2, and so on. Four additional surfaces complete the description of this illustrative and exemplary embodiment with object OB and image IM representing the planes, where in a lithographic apparatus the mask and the wafer are arranged. A surface designation is also made for the location of the aperture stop APE and intermediate image IMI. After each surface designation, there are two additional entries listing the vertex radius of curvature (R) and the vertex spacing between the optical surfaces. In this particular embodiment, each of the surfaces is rotationally symmetric conic surface with higher-order polynomial deformations. The aspheric profile is uniquely determined by its K, A, B, C, D, and E values. Each mirror uses 4th, 6th, 8th, 10th, and 12th order polynomial deformations. The sag of the aspheric surface (through 12th order) in the direction of the z-axis (z) is given by:

$$z = \frac{ch^2}{1+\sqrt{1-(1+k)c^2h^2}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12}$$

where h is the radial coordinate; c is the vertex curvature of the surface (1/R); and A, B, C, D, and E are the 4th, 6th, 8th, 10th, and 12th order deformation coefficients, respectively. These coefficients are listed in Table 2.

The optical system of this first preferred embodiment is designed to project a ring field format that is illuminated with extremely ultraviolet (EUV) or soft X-ray radiation. The numerical aperture NAO at the object OB is 0.050 radians; at a 4x

reduction this corresponds to a numerical aperture NA of 0.20 at the image IM. The ring field 21 at the object OB is shown with Figure 2. It is centered at 118 mm from the optical axis, which contains the vertex of each of the aspheric mirrors. This annular field extends from 114 mm to 122 mm forming an arcuate slit with a width 23 of 8 mm. The extent 25 of the ring field 21 perpendicular to the scan direction 27 becomes 104mm. The central field point is denoted with the reference sign 29. At 4x reduction, this ring field becomes 2.0 mm wide in the scan direction at the image.

As a result of the distribution of optical power and location of the aperture stop APE, the incidence angles are well controlled so that the design is compatible with EUV or soft X-ray multilayer coatings. As measured by the chief ray CR from the central field point 29, this system exhibits very low incidence angles ranging from 2.9° to 12.5°. The chief ray incidence angles for the chief ray CR from the central field point 29 are: Object: 5.2°; M1: 6.5°; M2: 5.0°; M3: 12.5°; M4: 5.6°, M5: 8.6°, and M6: 2.9°. These low incidence angles are a key enabling element for EUV lithography since (1) they minimize the multilayer induced amplitude and phase errors that have an adverse impact to lithographic performance and (2) enable simplified coating designs that do not rely heavily on the use of laterally graded coating profiles. With poor design (i.e., failure to minimize these incidence angles), these multilayer-induced amplitude and phase errors can lead to critical dimension (CD) errors that are easily greater than 20% of the nominal linewidth, making the system unusable for production applications.

Besides the low incidence angles, a preferred system further enables EUV lithography by utilizing mirrors with low peak aspheric departure. The maximum peak departure, contained on mirror M1, is 25.0 μm. The other mirrors have low-risk aspheres with departures that range from 0.5 μm to 14 μm. The low aspheric departures of the mirror surfaces facilitate visible light metrology testing without a null lens or Computer Generated Hologram CGH, resulting in surface figure testing to a high degree of accuracy. An aspheric mirror with a very large peak departure is

unproducible because it cannot be measured to the required accuracy to realize lithographic performance.

Table 3 summarizes the performance of the PPNPNP configuration of Fig. 1. The table demonstrates that this first preferred embodiment is able to achieve lithographic performance with a resolution on the order of 30 nm (assuming a k1-factor of approximately 0.5). The location of the aperture stop APE is selected so that the third order astigmatism contribution from the strong concave secondary mirror M2 is made very small.The strongly undercorrected astigmatic contribution from the primary mirror M1 comes from the aspheric departure on M1 and is balanced by the M3/M4 combination. Considering the system without any aspheres, the location of the aperture stop APE also effectively balances the third-order coma and distortion contributions from the primary mirror M1 and secondary mirror M2. A hyperbolic profile is added to the primary mirror M1 in such a way as to create a large undercorrected spherical contribution, coma contribution, and astigmatism contribution, thus promoting good aberration correction allowing the residual wavefront error (departure from the ideal reference sphere) to remain exceedingly small. In fact, aberration correction and resulting aberration balance reduces the composite RMS wavefront error is only 0.0125λ (0.17 nm), with simultaneous correction of the static distortion to less than 2 nm across the field.

This optical projection system has further benefits in that the system of Fig. 1 may be scaled in either numerical aperture or field. For example, it is desirable to scale this concept to larger numerical aperture to improve the modulation in the aerial image thus allowing 30 nm resolution with a less aggressive k1-factor. The results of a simple scaling experiment demonstrate that this preferred embodiment easily supports such scaling to larger numerical apertures. Without making any modifications, an analysis of the composite root mean square (RMS) wavefront error was made at a numerical aperture of 0.24, which represents a 20% increase to the value shown in Table 2. The composite RMS wavefront error was found to be 0.0287λ (0.38 nm), a level that supports lithographic quality imaging.

Referring to Fig. 2, it is desirable to increase the field of view in the scan direction to increase the number of wafers per hour (WPH) that the lithographic apparatus can process. The idea is that more area can be printed per unit time with a wider arcuate slit. The results of another simple scaling experiment demonstrate that this preferred embodiment easily supports increases in field width. Without making any modifications, an analysis of the composite RMS wavefront error was made over a 3 mm wide arcuate slit, which represents a 50% increase to the value shown in Table 2. The composite RMS wavefront error was found to be 0.0285λ (0.38 nm), again a level that supports lithographic quality imaging.

Second Preferred Embodiment:

In a second of these general embodiments, an optical projection system for extreme ultraviolet (EUV) lithography including six mirrors arranged in a PPNPNP configuration is disclosed. The plan view of this second preferred embodiment is shown in Figure 3, which demonstrates a PPNPNP configuration designed for EUV lithography at a wavelength of 13.4 nm. Like the first preferred embodiment, the system is reimaging, and unlike the '310 and '079 embodiments, locates the intermediate image IMI' before the second mirror pair. In this example, the intermediate image IMI' is located between mirror M2' and M3', helping to promote low incidence angle variation across mirror M5'. This construction also enables low mean incidence angles on mirror M1', M2', M4', and M6'. These low incidence angles are advantageous for maintaining good multilayer compatibility. The aperture stop APE' is located between M1' and M2' and is significantly spaced from either mirror, e.g., more than 200 mm.

In addition to the features outlined by the first preferred embodiment, this second preferred embodiment teaches that the tertiary mirror M3' may be located on the object side of the primary mirror M1' (i.e., closer to the object OB' than the primary mirror M1'). This feature departs drastically from the teaches of the prior art that

show the tertiary mirror must be located either in close proximity to the primary mirror('079 patent) or on the image side of the primary mirror('310 patent). This location of mirror M3' enables a reduction in the overall length from object plane OB to image plane IM (total track length) by some 250 mm. This decrease in total track length is accomplished by shifting the tertiary mirror from the image side of the primary mirror M1' to the object side of the primary mirror M1' and then decreasing the distance between mirror M1' and mirror M6'. This also allows the parent diameter of the tertiary mirror M3' to be smaller than either the primary mirror M1' or the secondary mirror M2'. These changes affect the angular condition of the chief rays upon reflection from the secondary mirror M2'. Prior art teaches that the chief ray from the central field point must diverge from the optical axis after reflection from the secondary mirror ('310 patent, '079 patent, etc.), but now the chief ray CR' assumes a more parallel condition with respect to the optical axis OA'. In this second embodiment, this chief ray CR' is made identically parallel to the optical axis OA'. This change in chief ray angle impacts the aberration balance in the design enough to form a distinct local minima, so that the residual aberration set seen in a Zernike decomposition of the wavefront differs from that of the first preferred embodiment.

The optical prescription of this second preferred embodiment of Fig. 3 is listed in Table 4 and Table 5. The aspheric mirror surfaces are labeled A(1)-A(6) in the tables with A(1) corresponding to mirror M1, A(2) corresponding to mirror M2, and so on.

Like the first preferred embodiment, the object OB' will be projected to the image IM' at 4x reduction in a ring field format with a telecentric imaging bundle (chief rays parallel to the optical axis OA' at the image IM'). Table 6 provides a performance summary demonstrating that this preferred embodiment is capable of lithographic performance at a wavelength of 13.4 nm. For comparison to the first embodiment, this second preferred embodiment also utilizes a numerical aperture NA of 0.20 at the image IM' and projects a 2 mm wide field in the scan direction. The system is compatible with reflective multilayer coatings since the incidence angles at

each mirror are relatively small. As measured by the chief ray CR' from the central field point 29', the incidence angles range from 3.9° to 14.6°. The exact chief ray incidence angles for the chief ray CR' from the central field point 29' are: Object OB': 5.6°; M1: 7.2°; M2: 4.4°; M3: 14.6°; M4: 8.8°, M5: 9.7°, and M6: 3.9°. Again, these low incidence angles are a key enabling element for EUV lithography since the low incidence angles minimize the multiplayer induced amplitude and phase errors that have an adverse impact to lithographic performance.

The composite RMS wavefront error across the field is 0.0131λ (0.18 nm), ranging from 0.0095λ (0.13 nm) at the best field point to 0.0157λ (0.21 nm) at the worst. The distortion of the chief ray has been reduced to less than 1 nm across the field. Clearly this combination of telecentric imaging, a highly corrected wavefront, and essentially no distortion demonstrates that this system is suitable for modern lithography at soft x-ray or extreme ultratviolet wavelengths.

This preferred embodiment has further advantages in that the system of Fig. 3 may be scaled in either numerical aperture or field to address even more advanced requirements. The results of a simple numerical aperture scaling experiment demonstrate that this preferred embodiment easily supports scaling to larger numerical apertures. Without making any modifications, an analysis of the composite root mean square (RMS) wavefront error was made at a numerical aperture of 0.22, which represents a 10% increase to the value shown in Table 4. The composite RMS wavefront error was found to be 0.027λ (0.36 nm), a level that supports lithographic quality imaging.

The results of another simple scaling experiment demonstrate that this preferred embodiment easily supports increases in field width. Without making any modifications, an analysis of the composite RMS wavefront error was made over a 3 mm wide arcuate slit, which represents a 50% increase to the value shown in Table 6. The composite RMS wavefront error was found to be 0.028λ (0.38 nm), again a level that supports lithographic quality imaging.

Third Preferred Embodiment:

The third preferred embodiment is shown in Fig. 4. Like the first and second preferred embodiments, this system utilizes a re-imaging PPNPNP configuration with a physically accessible aperture stop APE" that is located between the primary mirror M1" and secondary mirror M2". And like the first and second embodiments, the intermediate image IMI" is located between the secondary mirror M2" and the tertiary mirror M3". Similar to the second embodiment, the tertiary mirror M3" is located on the object side of the primary mirror M1". This particular embodiment differs from the second preferred embodiment in that the chief ray CR" from the central field point 29" converges toward the optical axis OA" after reflection from the secondary mirror M2", thus forming another advantageous projection system with distinct characteristics.

The optical prescription for this third embodiment of Fig. 4 is listed in Table 7 and Table 7. Table 7 lists the vertex radius of curvature as well as the separation between these mirrors along the optical axis. Each mirror is aspheric and labeled A(1)-A(6) in the tables with A(1) corresponding to mirror M1", A(2) corresponding to mirror M2", and so on. The prescription of the aspheric surface deformation per equation (1) is listed in Table 8. Taken together with the information provided in Table 9, an illustrative and exempary description of this prefered embodiment is disclosed.

Like the first two preferred embodiments, the object OB'', e.g. a pattern on mask or reticle, will be projected to the image IM'' at 4x reduction in a ring field format with a telecentric imaging bundle (chief rays parallel to the optical axis at the image). At the image'' typically a semiconductor wafer is arranged. Table 6 provides a performance summary demonstrating that this preferred embodiment is capable of lithographic performance at a wavelength of 13.4 nm. For comparison purposes, this third preferred embodiment also utilizes a numerical aperture NA of 0.20 at the image IM'' and projects a 2 mm wide field in the scan direction. The system is compatible with reflective multilayer coatings since the incidence angles at each mirror are relatively small. As measured by the chief ray CR'' from the central field point 29'', the incidence angles range from 3.9° to 13.9°. The exact chief ray incidence angles from the central field point are: Object OB'': 6.6°; M1: 8.0°; M2: 4.4°; M3: 13.9°; M4: 8.6°, M5: 9.6°, and M6: 3.9°. Again, these low incidence angles are a key enabling element for EUV lithography since the low incidence angles minimize the multiplayer induced amplitude and phase errors that have an adverse impact to lithographic performance.

The composite wavefront error across the field is 0.0203λ (0.27 nm), ranging from 0.0148λ (0.20 nm) at the best field point to 0.0243λ (0.33 nm) at the worst. The distortion of the chief ray has been reduced to less than 1 nm across the field. Clearly this combination of telecentric imaging, a highly corrected wavefront, and essentially no distortion demonstrates that this system is suitable for modern lithography at soft x-ray or extreme ultratviolet wavelengths. The design can also be scaled in numerical aperture or field like second preferred embodiment.

The optical design descriptions provided above for the first-third embodiments herein demonstrate an advantageous catoptric projection system concept for EUV lithography. While these embodiments have been particularly described for use in a 13.4 nm tool, the basic concept is not limited to use with lithographic exposure tools at this wavelength, either shorter or longer, providing a suitable coating material exists in the soft x-ray region of the electromagnetic spectrum.

While exemplary drawings and specific embodiments of the present invention have been described and illustrated, it is to be understood that that the scope of the present invention is not to be limited to the particular embodiments discussed. Thus, the embodiments shall be regarded as illustrative rather than restrictive, and it should be understood that variations may be made in those embodiments by workers skilled in the arts without departing from the scope of the present invention as set forth in the claims that follow, and equivalents thereof. For example, one skilled in the art may reconfigure the embodiments described herein to expand the field of view, increase the numerical aperture, or both, to achieved improvements in resolution or throughput.

Table 1. Optical prescription first preferred embodiment

Element number	Vertex radius of curvature	Thickness (mm)	Glass
Object OB	INFINITY	806.775	
A(1)	-1997.63	-328.184	REFL
Aperture Stop APE	INFINITY	-399.404	
A(2)	1148.069	649.7918	REFL
Intermediate image IMI	INFINITY	132.9323	
A(3)	486.7841	-277.569	REFL
A(4)	660.9159	890.6587	REFL
A(5)	393.8628	-476.472	REFL
A(6)	580.3377	501.472	REFL
Image IM			

Table 2. Aspheric prescription

Aspheric	K	A	B	C	D	E
A(1)	-9.1388E+01	5.4676E-10	7.0301E-15	-1.4409E-19	2.1657E-25	5.5712E-30
A(2)	-6.4930E-01	3.7924E-11	3.2952E-18	-1.1462E-21	8.4115E-26	-4.9020E-30
A(3)	-2.3288E-01	3.3571E-10	1.8240E-14	-1.9218E-19	-4.2667E-23	2.9468E-27
A(4)	-6.4180E-03	3.9345E-11	1.8257E-16	-6.9023E-22	1.3692E-26	-6.2042E-32
A(5)	1.5857E+00	-1.7764E-09	7.7970E-14	-1.2619E-18	5.4017E-22	-3.8012E-26
A(6)	8.9884E-02	-4.2455E-12	1.4898E-17	1.4824E-22	-7.0550E-28	6.6775E-32

Table 3. Performance summary first preferred embodiment

Metric	Performance
Wavelength	13.4 nm
Numerical aperture (image)	0.20
Ringfield format (image) i. Radius ii. Width iii. Chord	 30.0 mm 2.0 mm 26.0 mm
Reduction ratio (nominal)	4:1
Overall length (mm)	1500 mm
RMS wavefront error (waves @ λ = 13.4 nm) i. Composite ii. Variation	 0.0125λ 0.0076λ - 0.0167λ
Chief ray distortion (max)	1.9 nm
Exit pupil location	Infinity
Max. aspheric departure across instantaneous clear aperture (ICA) i. M1 ii. M2 iii. M3 iv. M4 v. M5 vi. M6	 25.0 μm 0.5 μm 1.4 μm 14.0 μm 3.0 μm 3.8 μm

Table 4. Optical prescription second preferred embodiment

Element number	Vertex radius of curvature	Thickness (mm)	Glass
Object Plane OB'	INFINITY	786.7828	
A(1)	-1522.9647	-275.3849	REFL
Aperture Stop APE'	INFINITY	-461.3979	
A(2)	922.8035	452.3057	REFL
Intermediate image IMI'	INFINITY	95.0000	
A(3)	273.0204	-218.5016	REFL
A(4)	511.1320	834.1959	REFL
A(5)	434.1472	-326.2172	REFL
A(6)	440.9571	363.2172	REFL
Image IM'			

Table 5. Aspheric prescription second preferred embodiment

Aspheric	K	A	B	C	D	E
A(1)	-6.5661E-04	3.6028E+01	2.7656E-09	1.3237E-14	5.6475E-20	1.4711E-23
A(2)	1.0837E-03	-3.0142E+00	3.2384E-10	-6.8499E-16	-1.8748E-20	1.0985E-24
A(3)	3.6627E-03	1.9328E+00	-1.6611E-08	-4.9082E-13	2.9169E-17	-3.8673E-21
A(4)	1.9564E-03	-1.2442E-01	-1.0927E-11	2.7712E-16	-2.0608E-21	3.6395E-26
A(5)	2.3034E-03	8.5377E+00	-6.9001E-09	-2.2929E-13	-8.9645E-18	-2.1791E-21
A(6)	2.2678E-03	1.4526E-01	3.2069E-11	3.3003E-16	5.1329E-21	-1.7296E-25

Table 6. Performance summary second preferred embodiment

Metric	Performance
Wavelength	13.4 nm
Numerical aperture (image)	0.20
Ringfield format (image)	
i. Radius	30.0 mm
ii. Width	2.0 mm
iii. Chord	26.0 mm
Reduction ratio (nominal)	4:1
Overall length (mm)	1250
RMS wavefront error (waves @ λ = 13.4 nm)	
i. Composite	0.0131λ
ii. Variation	0.0095λ - 0.0157λ
Chief ray distortion (max)	0.9 nm
Exit pupil location	Infinity
Max. aspheric departure across instantaneous clear aperture (ICA)	
i. M1'	18.0 μm
ii. M2'	6.2 μm
iii. M3'	8.7 μm
iv. M4'	28.0 μm
v. M5'	7.0 μm
vi. M6'	7.0 μm

Table 7. Optical prescription third preferred embodiment

Element number	Vertex radius of curvature	Thickness (mm)	Glass
Object OB''	INFINITY	708.2375	
A(1)	-1351.9353	-222.3328	REFL
Aperture Stop APE''	INFINITY	-435.9047	
A(2)	801.1198	389.5537	REFL
Intermediate image IMI''	INFINITY	85.9324	
A(3)	257.6903	-223.6826	REFL
A(4)	508.9915	827.9429	REFL
A(5)	434.7744	-321.5090	REFL
A(6)	436.7586	358.5090	REFL
Image IM''			

Table 8. Aspheric prescription third preferred embodiment

Aspheric	K	A	B	C	D	E
A(1)	-7.3968E-04	1.8042E+00	2.2388E-09	4.0136E-15	6.8479E-19	-1.2865E-22
A(2)	1.2483E-03	-2.6267E+00	4.4819E-10	-1.7571E-15	5.8143E-20	-3.7874E-24
A(3)	3.8806E-03	-8.5604E-01	2.2165E-08	-6.7204E-12	1.1406E-15	-1.0131E-19
A(4)	1.9647E-03	-7.7387E-02	-3.8053E-11	-1.2483E-15	2.8880E-20	-3.4746E-25
A(5)	2.3000E-03	8.3687E+00	-6.1944E-09	-1.9683E-13	-1.6280E-17	4.8296E-21
A(6)	2.2896E-03	1.3269E-01	5.6594E-11	5.5533E-16	-1.1978E-21	7.3097E-25

Table 9. Performance summary third preferred embodiment

Metric	Performance
Wavelength	13.4 nm
Numerical aperture (image IM")	0.20
Ringfield format (image IM") i. Radius ii. Width iii. Chord	 30.0 mm 2.0 mm 26.0 mm
Overall length (mm)	1156
Reduction ratio (nominal)	4:1
RMS wavefront error (waves @ λ = 13.4 nm) i. Composite ii. Range	 0.0203λ 0.0148λ - 0.0243λ
Chief ray distortion (max)	1.5 nm
Exit pupil location	Infinity
Max. aspheric departure across instantaneous clear aperture (ICA) i. M1" ii. M2" iii. M3" iv. M4" v. M5" vi. M6"	 17.3 µm 6.4 µm 9.7 µm 32.2 µm 6.7 µm 6.7 µm

WHAT IS CLAIMED IS:

1. An EUV optical projection system, comprising:
at least six reflecting surfaces for imaging an object (OB, OB', OB") on an image (IM, IM', IM"), and wherein said system is configured to form an intermediate image (IMI, IMI', IMI") along an optical path from the object (OB, OB', OB") to the image (IM, IM', IM") between a secondary mirror (M2, M2', M2") and a tertiary mirror (M3, M3', M3"), such that a primary mirror (M1, M1', M1") and the secondary mirror (M2, M2', M2") form a first optical group (G1, G1', G1") and the tertiary mirror (M3, M3', M3") and a fourth mirror (M4, M4', M4"), a fifth mirror (M5, M5', M5") and a sixth mirror (M6, M6', M6") form a second optical group (G2, G2', G2"), and wherein said secondary mirror (M2, M2', M2") is concave, and wherein said tertiary mirror (M3, M3', M3") is convex.

2. The system according to Claim 1, further comprising an aperture stop (APE, APE', APE") located along said optical path from said object (OB, OB', OB") to said image (IM, IM', IM") between said primary mirror (M1, M1', M1") and said secondary mirror (M2, M2', M2").

3. The system according to Claim 1 or 2, wherein said aperture stop (APE, APE', APE") is not located on said first mirror (M1, M1', M1") and said aperture stop (APE, APE', APE") is not located on said second mirror (M2, M2', M2").

4. The system according to at least one of the preceding claims, wherein an optical axis (OA") is defined between an object plane and an image plane, and wherein said system is further configured such that a chief ray (CR") from a central field point (29) converges toward said optical axis (OA") while propagating between said secondary mirror (M2") and said tertiary mirror (M3").

5. The system according to at least one of the claims 1 to 3, wherein an optical axis (OA') is defined between an object plane and an image plane, and wherein said system is further configured such that a chief ray (CR') from a central field point (29) propagates approximately parallel to said optical axis (OA') while propagating between said secondary mirror (M2') and said tertiary mirror (M3').

6. The system according to at least one of the preceding claims , wherein said tertiary mirror (M3', M3") along said optical path from said object (OB', OB") to said image (IM', IM") is physically located closer to said object (OB', OB") than said primary mirror (M1', M1").

7. The system according to at least one of the claims 1 to 3, wherein an optical axis (OA) is defined between a object plane and a image plane, and wherein said system is further configured such that a chief ray (CR) from a central field point (29) diverges away from said optical axis (OA) while propagating between said secondary mirror (M2) and said tertiary mirror (M3).

8. The system according to at least one of the preceding claims, wherein said primary mirror (M1) along said optical path from said object (OB) to said image (IM) is physically located closer to said object (OB) than said tertiary mirror (M3).

9. The system according to at least one of the preceding claims, wherein said primary mirror (M1, M1', M1") is concave, said fourth mirror (M4, M4', M4") is concave, said fifth mirror (M5, M5', M5") is convex and said sixth mirror (M6, M6', M6") is concave.

10. The system according to at least one of the preceding claims, wherein each of said six reflecting surfaces is disposed between said object (OB, OB', OB") and

said image (IM, IM', IM"), and wherein a physical distance between said object (OB, OB', OB") and said image (IM, IM', IM") is substantially 1500 mm or less.

11. The system according to at least one of the preceding claims, wherein each of said six reflecting surfaces is disposed between said object (OB") and said image (IM"), and wherein a physical distance between said object (OB") and said image (IM") is substantially 1200 mm or less.

12. The system according to at least one of the preceding claims, wherein said system has a numerical aperture greater than 0.18 at the image (IM, IM', IM").

13. The system according to at least one of the preceding claims, wherein each of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 15°, preferably less than substantially 13°.

14. The system according to at least one of the preceding claims, wherein five of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 11°, preferably less than substantially 9°.

15. The system according to at least one of the preceding claims, wherein said system is configured to have a RMS wavefront error of 0.017λ or less.

16. The system according to at least one of the preceding claims, wherein said system is configured to have a RMS wavefront error of between 0.017λ and 0.011λ.

17. An EUV optical projection system, comprising: at least six reflecting surfaces for imaging an object (OB, OB', OB") on an image (IM, IM', IM"), and wherein said system is configured to form an intermediate image (IMI, IMI', IMI") along an optical path from the object (OB, OB', OB") to the image (IM, IM', IM") between a secondary mirror (M2, M2', M2") and a tertiary mirror (M3, M3', M3"), such that a primary mirror (M1, M1', M1") and the secondary mirror (M2, M2', M2") form a first optical group (G1, G1', G1") and the tertiary mirror (M3, M3', M3") and a fourth mirror (M4, M4', M4"), a fifth mirror (M5, M5', M5") and a sixth mirror (M6, M6', M6") form a second optical group (G2, G2', G2"), and wherein each of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 15°, preferably less than substantially 13°, and wherein said system has a numerical aperture greater than 0.18 at the image (IM, IM', IM").

18. The system according to Claim 17, wherein five of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 11°, preferably less than substantially 9°.

19. The system according to Claim 17 or 18, wherein an optical axis is defined between an object plane and an image plane, and wherein said system is further configured such that a chief ray (CR") from a central field point (29) converges toward said optical axis (OA") while propagating between said secondary mirror (M2") and said tertiary mirror (M3").

20. The system according to at least one of the claims 17 to 19, wherein said tertiary mirror (M3', M3") along said optical path from said object (OB', OB") to said image (IM', IM") is physically located closer to said object (OB', OB") than said primary mirror (M1', M1").

21. The system according to at least one of the claims 17 to 19, wherein an optical axis (OA) is defined between a object plane and a image plane, and wherein said system is further configured such that a chief ray (CR) from a central field point (29) diverges away from said optical axis (OA) while propagating between said secondary mirror (M2) and said tertiary mirror (M3).

22. The system according to at least one of the claims 17 to 21, wherein said primary mirror (M1) along said optical path from said object (OB) to said image (IM) is physically located closer to said object (OB) than said tertiary mirror (M3).

23. The system according to at least one of the claims 17 to 22, wherein said secondary (M2, M2', M2") mirror is concave, and wherein said tertiary mirror (M3, M3', M3") is convex.

24. The system according to at least one of the claims 17 to 23, wherein each of said six reflecting surfaces is disposed between said object (OB, OB', OB") and said image (IM, IM', IM"), and wherein a physical distance between said object (OB, OB', OB") and said image (IM, IM', IM") is substantially 1500 mm or less.

25. The system according to at least one of the claims 17 to 24, wherein each of said six reflecting surfaces is disposed between said object (OB") and said image (IM"), and wherein a physical distance between said object (OB") and said image (IM") is substantially 1200 mm or less.

26. An EUV optical projection system, comprising:
at least six reflecting surfaces for imaging an object (OB, OB', OB") on an image (IM, IM', IM"), and an aperture stop (APE, APE', APE") located along an optical

path from said object (OB, OB', OB") to said image (IM, IM', IM") between a primary mirror (M1, M1', M1") and a secondary mirror (M2, M2', M2"), and wherein said secondary mirror (M2, M2', M2") is concave, and wherein said tertiary mirror (M3, M3', M3") is convex.

27. The system according to Claim 26, wherein said aperture stop (APE, APE', APE") is not located on said first mirror (M1, M1', M1") and said aperture stop (APE, APE', APE") is not located on said second mirror.

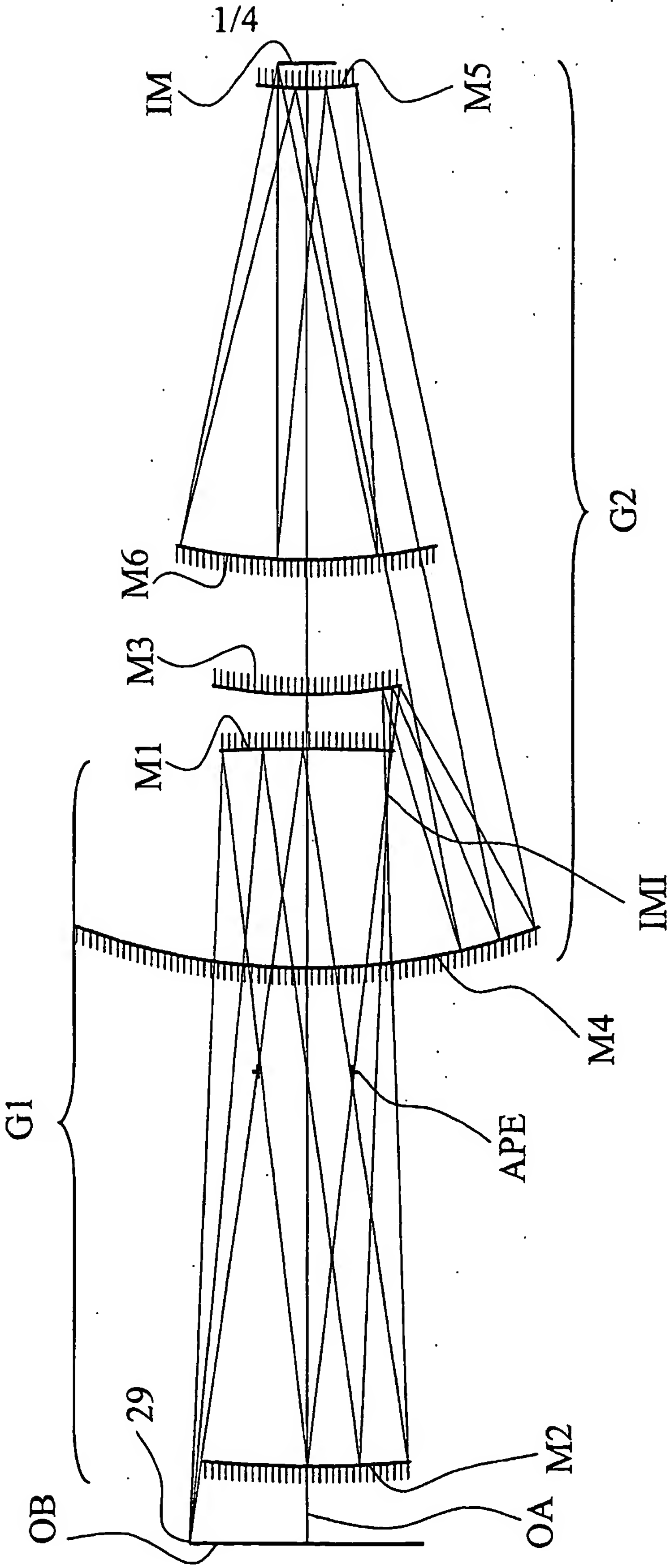
28. The system according to Claim 26 or 27, wherein each of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 15°, preferably less than substantially 13°.

29. The system according to at least one of the claims 26 to 28, wherein five of the six reflecting surfaces receives a chief ray (CR, CR', CR") from a central field point (29) at an incidence angle of less than substantially 11°, preferably less than substantially 9°.

30. An EUV optical projection system, comprising: at least six reflecting surfaces for imaging an object (OB") on an image (IM"), andan aperture stop (APE") located along an optical path from said object (OB") to said image (IM") between a primary mirror (M1") and a secondary mirror (M2"), and wherein said system is configured such that a chief ray (CR") from a central field point (29) converges toward said optical axis (OA) while propagating between said secondary mirror (M2") and a tertiary mirror (M3").

31. The system according to Claim 30, wherein said tertiary mirror (M3") along said optical path from said object (OB") to said image (IM") is physically located closer to said object (OB") than said primary mirror (M1").

FIG.1



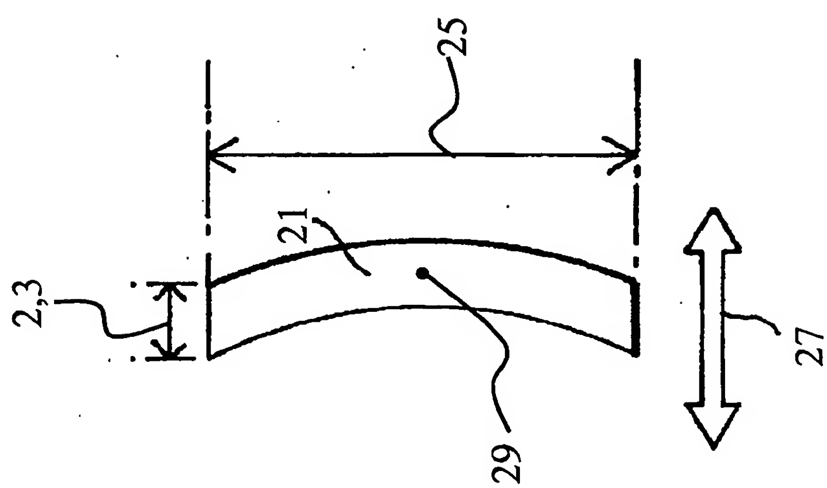


FIG.2

FIG.3

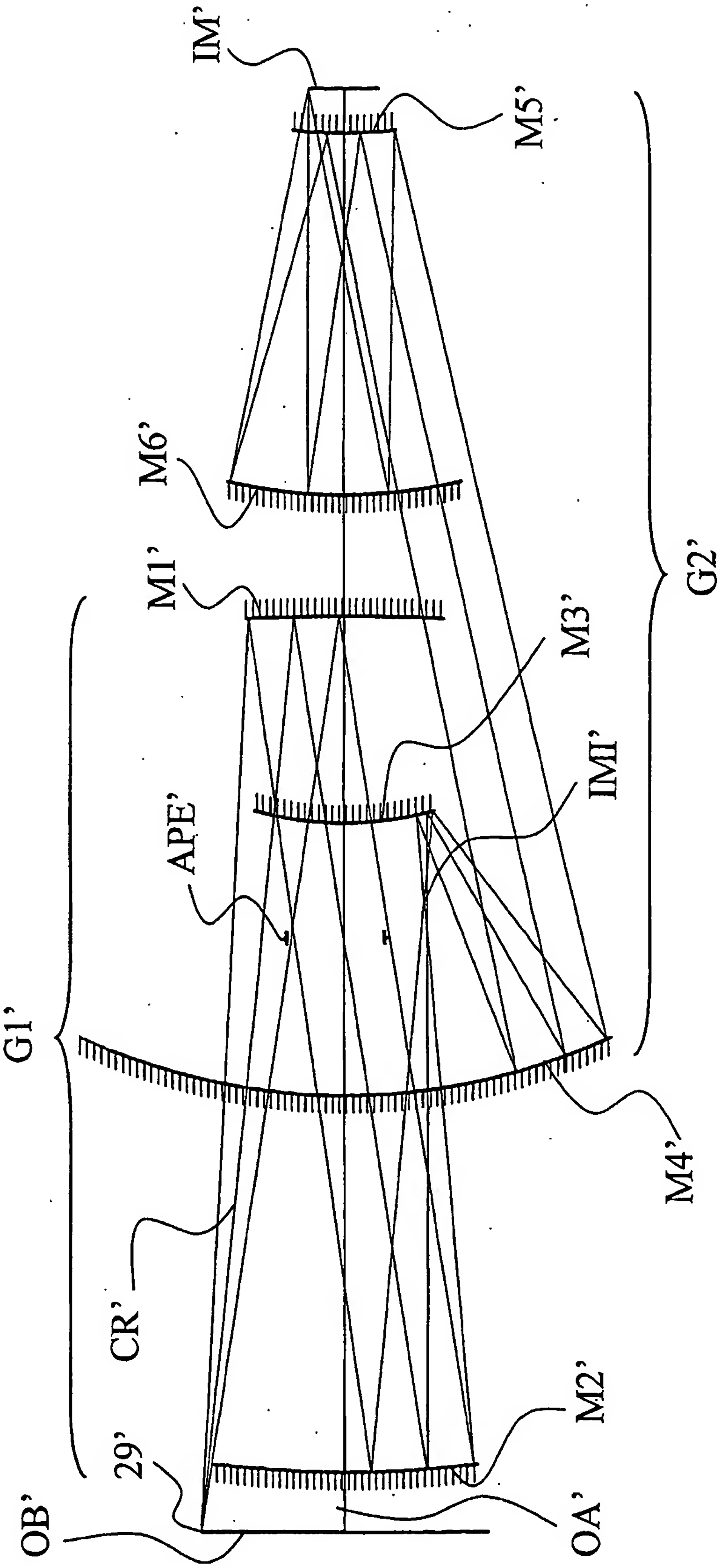


FIG.4